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Forage frost protection potential of conifer silvopastures

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Abstract

In temperate climates, forages are frequently held in a near dormant state at both ends of the growing season due to episodic radiation frost. During these periods, air temperature is frequently adequate for forage growth to supply feed for grazing animals. The effect of thermal radiation from conifer tree canopies on forage canopy temperature was evaluated for a silvopasture with variable tree density. A long-wave radiation-sensitive sensor for measuring temperature at the forage canopy level was designed, tested, and used to approximate night time forage canopy temperature during the autumn of 1999 and 2000 and spring of 2000. Temperature from the designed sensor correlated linearly with forage canopy temperature measured with an infrared thermometer with a slope of 1.0, a 0.9 °C offset, and an r^2 of 0.999. The response of sensor temperature to night sky shading by trees was also linear. Under 77% tree cover sensor temperature remained within half a degree of air temperature, however, under 7% cover averaged 10.4 °C below air temperature during radiation frost events. The results of this study indicate that a well designed silvopasture can potentially extend the grazing season period on both ends in regions were radiation frosts are prevalent.
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Keywords: Agroforestry; Microclimate; Nighttime; Temperature; Radiation frost; Shade

1. Introduction

Agricultural production in temperate climate areas is constrained by cold weather which limits the growing season. Radiation frosts frequently injure vegetation early and late in the growing season even when air temperature is warm enough to maintain plant health. Radiation frost occurs at night when clear sky conditions result in a large net loss in long-wave radiation from plant surfaces and a lack of wind minimizes convective heat gain from air.

Obstructing the open sky from a plant's upward field-of-view is one strategy for reducing the severity of radiation frost by providing a surface much warmer than open sky with which plants exchange long-wave radiation. Shade cloth mounted over vegetation is effective for reducing radiation frost, however, the cost limits its use to protection of high value products (Stamps, 1989; Igarashi et al., 1993; Teitel et al., 1996; Scowcroft et al., 2000).

Trees can provide an economical interface between crops and open sky that minimizes damage from radiation frost. Overstory trees are effectively used to prevent frost damage on coffee crops south of 20° latitude in South America (Caramori et al., 1996). In northern Europe, birch shelterwoods provide conifer saplings with some frost protection (Odin et al., 1984). While an analysis of tree overstory benefits on forage production has not been made, there have been observations of improved forage growth under conifer trees during cold weather (Sibbald et al., 1991; Brazoptos and Papanastasis, 1995).

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The objective of this project is to quantify the relationship between tree canopy density in a conifer silvopasture and the severity of radiation frost.

2. Theoretical consideration

Net radiation, which is a major driver of plant climate, is most simply defined by

$$R_n = R_i - R_o \tag{1}$$

where R_i (W m^{-2}) is incoming radiation and R_o (W m^{-2}) is outgoing radiation. During the daytime, both of these components contain short-wave and long-wave radiation. At night, however, the short-wave components are equal to zero.

The outgoing long-wave radiation from a surface is defined by the Stefan–Boltzmann equation as

$$R_o = \sigma\varepsilon T^4 \tag{2}$$

where σ is the Stefan–Boltzmann constant (5.6697×10^{-8} W m^{-2} K^{-4}), ε the thermal emissivity which is a dimensionless factor between 0 and 1 quantifying the efficiency with which a surface emits thermal radiation, and T is the surface temperature (K).

Nighttime incoming long-wave radiation can be defined as

$$R_i = m_c R_c + (1 - m_c) R_a \tag{3}$$

where m_c is the fractional cloud cover, R_c (W m^{-2}) the radiation emitted from clouds, and R_a (W m^{-2}) is the radiation emitted from open sky. R_c is a function of cloud type and temperature of the lower cloud region. Dense clouds, which have an ε value near 1, generally have a bottom surface temperature within a couple of degrees of ground temperature (Campbell, 1977), thus, net radiation approaches zero.

When clouds are absent, radiation from open sky is dependent on air temperature and water vapor content. Due to the difficulty in making good incoming radiation measurements, a number of empirical equations have been developed. One which is accurate even at low air temperatures was developed by Satterlund (1979) yielding

$$R_k = (\sigma T_a^4)1.08[1 - \exp(-e_a^{T_a/2016})] \tag{4}$$

where T_a is air temperature (K) and e_a is ambient vapor pressure (mbar). Assuming outgoing radiation is from a forage canopy (R_f) at the temperature, T_f, a minimal difference between R_k and R_f is a necessary condition for radiation frost. An effective sky temperature (T_k) can be calculated using the Stefan–Boltzmann equation (Eq. (4)) and assuming ε is equal to 1.

In a silvopastoral system, understory forages receive an additional long-wave energy input from the tree overstory. As a result, under clear sky conditions conducive to radiation frost, incoming long-wave radiation at the forage level is calculated using an equation similar to Eq. (3) except tree long-wave is substituted for cloud long-wave giving

$$R_i = m_t R_t + (1 - m_t) R_k \tag{5}$$

where m_t is the fraction of the sky obscured by trees and R_t (W m^{-2}) is the long-wave input from trees. Tree radiation input is calculated from the temperature of tree foliage, T_t (K), using the Stefan–Boltzmann equation (Eq. (2)) and assuming ε for conifer trees is 0.97 (Lee, 1978).

Net radiation can therefore be calculated for any point within a conifer silvopasture by combining Eqs. (1), (2), (4) and (5) to give

$$R_n = m_t\sigma\varepsilon T_t^4 + (1 - m_t)(\sigma T_a^4)1.08 \times [1 - \exp(-e_a^{T_a/2016})] - \sigma\varepsilon T_f^4. \tag{6}$$

3. Materials and methods

The research site is a 0.7 ha area of 35-year-old, 17 m tall, mixed conifers on a farm site in southern West Virginia (37°46′W latitude 81°00′N longitude 860 m elevation). The site is dominated by white pine (*Pinus strobus* L.) and red spruce (*Picea rubens* Sarg.) with a few scattered pitch pine (*Pinus rigida* Mill.) and short-leaf pine (*Pinus echinata* Mill.). The trees are growing on a Gilpin soil (fine loamy, mixed, mesic Typic Hapludult). The understory vegetation is dominated by orchardgrass (*Dactylis glomerata* L.) and grazed periodically by sheep to maintain a canopy height between 5 and 15 cm.

Tree senescence over the years has left areas of the stand thinned and several large gaps, the largest of which was 10% of the total area. This resulted in a range of tree canopy closure ranging from nearly complete to large overheads openings. Percent canopy

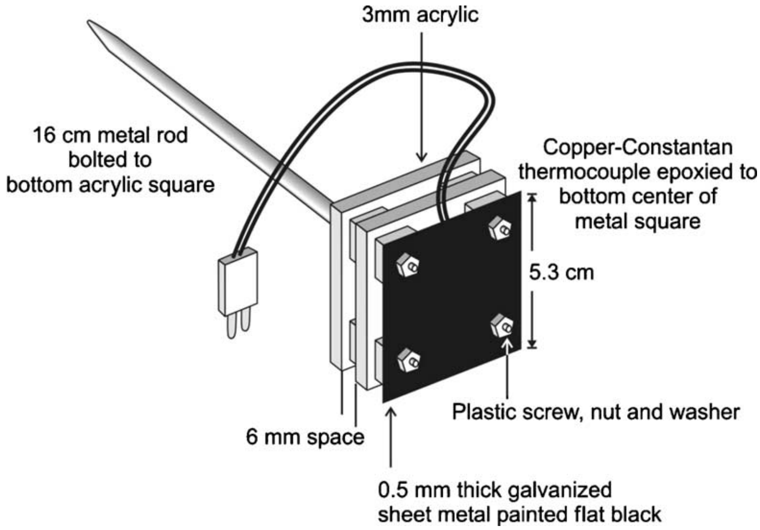

Fig. 1. Schematic showing design of the radiation frost potential (RFP) sensor.

closure of measurement sites was determined using a digital camera with hemispheric lens and images analyzed using the black and white manual option of WinSCANOPY software (Instruments Regent Inc., Que., Canada).

A simple, inexpensive sensor was designed to allow measuring the radiation frost potential (RFP) at multiple locations within the research site simultaneously. It consists of a thin, flat-black metal platelet thermally isolated from the metal rod pushed into the ground for placement (Fig. 1) at the height of the top grass canopy (maintained about 10 cm). The platelet was installed in the field so it was oriented horizontally, and thus, in equilibrium with long-wave radiation from the hemispherical field-of-view. The RFP temperature (T_r) was measured by a copper–constantan thermocouple attached to the bottom center. The sensor is designed to estimate forage canopy temperature only at night which is when radiation frosts occur. For calculation of nighttime long-wave radiation emitted by the sensor the Stefan–Boltzmann equation (Eq. (4)) was used with an ε of 0.99 (Buettner and Kern, 1965).

At each measurement, location within the silvopasture two RFP sensors were installed along with two thermocouples pressed into the soil surface for measuring surface soil temperature (T_s). Sensors were wired into a Campbell AM416-multiplexor and subsequently into a Campbell 21X-datalogger. Measurements were made every 10 s and saved as 15 min averages. Canopy temperature of grass adjacent to one RFP sensor pair was measured at the same time intervals with an Everest 4001 infrared temperature transducer for validation of RFP sensor data under varying climate conditions. Air temperature was also measured at 14 m height using a thermocouple inside a white plastic radiation shields and tied to a rope threaded through a pulley mounted in a central tree. The 14 m height was well within the foliage and that temperature was used to calculate long-wave radiation emitted from foliage. Wind was measured at 0.3 m using a R.M. Young 03101-5 anemometer.

In addition to being installed within the tree stand, a set of sensors were installed in an open treeless pasture adjacent to the silvopasture. A weather station was also located at this site and air temperature and relative humidity data from the sensors mounted at 2 m were used to calculate open sky temperature.

Data were collected during the autumn of 1999 and 2000 and spring of 2000. Collection dates were from early October to early December in the autumn and from mid March to late April in the spring. These represent the periods when radiation frost can limit forage production for the area.

Net radiation difference between sites was analyzed using a mixed model (Littell et al., 1996) analysis of variance which specified a compound symmetry form for the variance–covariance matrix that accounts for autocorrelation caused by measuring the same sites across different dates.

4. Results and discussion

The tree canopy cover ratios (m_t), determined using the WinSCANOPY software, for the sky field-of-view at the eight silvopasture sensor sites were 0.77, 0.77, 0.75, 0.74, 0.70, 0.65, 0.60, and 0.55. These values represent the range of tree canopy cover within the conifer stand. The m_t value for the adjacent field site without trees was 0.07 rather than 0 due to distant horizon obstruction.

The RFP sensors gave temperature values highly correlated with actual grass canopy temperature measured with the Everest 4001 infrared thermometer. The response was linear across all nighttime sky conditions between 22:00 and 5:00 (Fig. 2). The RFP sensor consistently gave temperature values 0.9 °C higher than the Everest 4001 sensor across the total temperature range. Since the Everest 4001 sensor integrates temperature from leaves throughout the canopy depth that are within the field-of-view, the difference may be due to the RFP sensor only representing the temperature experienced by the uppermost leaves. However, since the difference is small and consistent, there can be confidence that RFP sensors give a reliable measure of differences between locations relative to tree canopy cover.

The RFP temperature for all sites, even with widely differing m_t values, converged on heavily overcast nights (Fig. 3) (24 October 1999), however, striking differences were evident under clear sky conditions (29 October 1999). Sensors at sites with greater amounts of open sky were much cooler on clear nights and also warmer in the daytime due to solar radiation impacting the black sensor surface (although the daytime data is not relevant to this study).

The Appalachian region is typically at least partly cloudy. To get temperature trends for typical radiation frost conditions, 16 nights with the largest temperature differences between sites were chosen for analysis (Table 1). Four 15 min values from the coldest hour were averaged for each respective night. Open sky temperature, calculated using Eq. (4), averaged 19.5 °C colder than the air temperature within the tree canopy for the 16 nights. The air temperature at 14 m, within the tree canopy, averaged <1 °C warmer than the 2 m air temperature at the weather station in the adjacent open field. This suggests that the vertical temperature gradient above 2 m was minimal and the mid canopy air temperature gave a reasonable value from which to calculate thermal radiation emitted toward the grass understory.

The open field ($m_t = 0.07$) RFP temperatures averaged 10.4 °C colder than air temperature while under

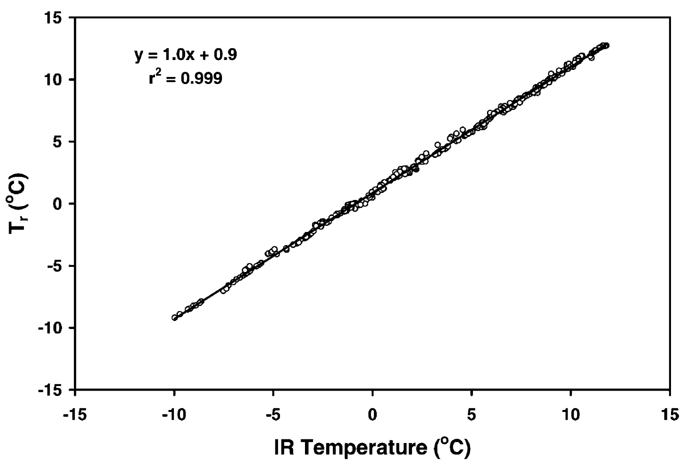

Fig. 2. RFP sensor temperature as a function of simultaneous infrared thermometer temperature of adjacent forage from 22:00 to 5:00 for the period 18 October to 3 December 1999.

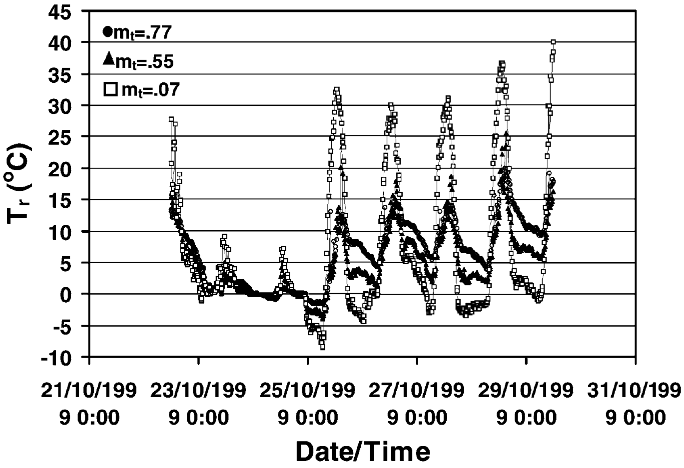

Fig. 3. Continues 15 min RFP sensor temperature averages for the week of 22 October to 30 October 1999 for sites, where m_t = 0.07, 0.55, and 0.77.

dense forest canopy (m_t = 0.77) the RFP temperature was only 0.4 °C colder than air temperature. The response of RFP temperature relative to open sky was linear for the range of m_t for the eight sites within the silvopasture, and one adjacent pasture site, with a 10 °C increase in temperature at the maximum value for m_t (0.77) compared to the open field (Fig. 4). There was an average range of 3.3 °C difference within the silvopasture as a result in variation in tree cover.

The conclusion of the analysis of variance for net radiation shows an insignificant F-value for differences between sites. However, when compared using the Tukey's HSD test, the site means show some separation at the P = 0.05 levels (Table 2). The most

Table 1

Time, spatially averaged surface soil temperature, air temperature and relative humidity for the coldest period during radiation frost events with calculated sky temperature, measured air temperature within tree foliage, RFP temperature for sites, where m_t = 0.07, 0.55, 0.77, and wind

Date	Hours	T_s (°C)	T_a (°C)	R.H. (%)	T_k (°C)	T_t (°C)	$T_{0.07}$ (°C)	$T_{0.55}$ (°C)	$T_{0.77}$ (°C)	Wind (m s^{-1})
29 October 1999	5	8.8	9.8	57	−6.0	12.1	−0.5	6.3	10.3	
8 November 1999	2	5.7	4.2	46	−14.6	4.6	−6.0	−0.7	3.8	
9 March 2000	0	10.0	17.4	28	−0.4	18.1	7.3	15.1	17.1	1.21
13 March 2000	5	0.4	−6.7	71	−25.9	−6.0	15.2	−9.1	−6.7	0.04
14 March 2000	3	1.7	0.9	46	−18.6	1.2	−9.3	−2.1	0.3	0.13
26 March 2000	23	6.8	9.3	26	−10.9	10.9	−5.8	6.4	10.1	0.58
31 March 2000	5	3.3	1.5	62	−16.6	2.1	−10.0	−2.3	1.1	0.04
1 April 2000	4	3.6	4.7	33	−15.5	5.2	−5.4	1.3	3.7	0.09
12 October 2000	5	8.0	6.1	54	−11.5	7.2	−2.4	2.6	6.0	0
13 October 2000	3	9.3	10.8	37	−7.4	11.9	−0.9	6.9	9.7	0.09
14 October 2000	2	10.2	12.5	33	−5.8	13.9	1.6	8.3	11.8	0
29 October 2000	5	8.8	3.4	72	−13.6	3.3	−6.9	−1.5	2.0	0.13
30 October 2000	4	6.8	2.7	49	−16.2	2.5	−7.3	−2.2	1.9	0
31 October 2000	5	7.1	4.5	45	−14.3	5.6	−3.5	2.7	5.1	1.21
1 November 2000	5	7.4	7.1	33	−12.6	7.2	−4.3	1.5	5.9	0
2 November 2000	2	8.6	10.0	29	−11.3	10.8	−0.8	5.8	8.9	0
Average		6.7	6.1	45	−12.6		6.9	−4.3	2.4	5.7

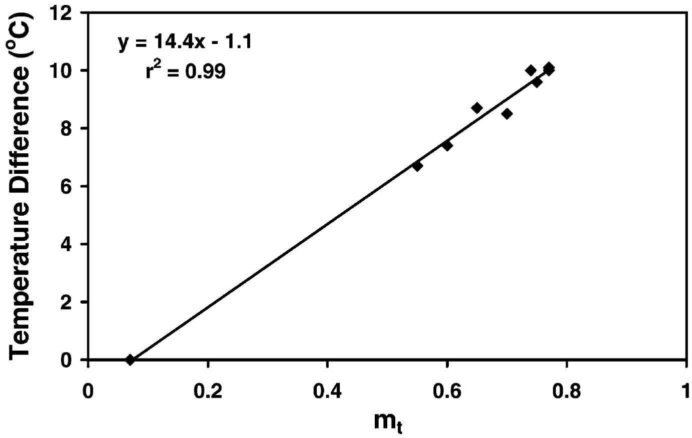

Fig. 4. Differences between RFP temperature at $m_t = 0.07$ and all respective sites as a function of m_t.

obvious conclusion is that all the first eight sites are significantly different from the last site which was the open field site. As far as the correlation with m_t, there was no significant correlation among the silvopasture sites. When the open field site was included, there was a significant correlation, but this was because there were basically "two" points, the open field site and the silvopasture cluster.

Clear sky, still air, night net radiation levels are very low compared to typical daytime values (20–30 W m^{-2} at night compared to 500–600 W m^{-2} during sunny midday). Largest absolute nighttime net radiation values can be expected when there is the largest temperature difference between plant canopy and open sky. This happens when there are clear sky conditions and low humidity coupled with high wind. The wind prevents formation of a stable boundary layer at the surface, thus, maximizing sensible heat flux to the surface.

Table 2
Amount of sky obscured by tree foliage (m_t) and average net radiation at each measurement site for the 16 radiation frost events

Site	m_t	R_n* (W m^{-2})
1	0.70	−20 a
2	0.75	−21 ab
3	0.77	−22 b
4	0.77	−22 b
5	0.60	−22 b
6	0.55	−23 bc
7	0.74	−24 cd
8	0.65	−24 d
9	0.07	−28 e

* Values followed by the same letter are not significantly ($P >$ 0.05) different by Tukey's HSD test.

The RFP temperature for all silvopasture sites was uniformly 4–5 °C warmer than the calculated overhead sky-tree field-of-view temperature in spite of the 3.3 °C sensor difference between sites (Fig. 5). Within the silvopasture, wind averaged <0.1 m s^{-1} at the 0.3 m elevation for 10 of the 14 nights measured with only two nights exceeding 1 m s^{-1} (Table 1). The near constant difference between the RFP temperature and the overhead field-of-view temperature is curious since a larger temperature gradient between the RFP sensor and the air above it could increase the sensible heat flux, thus, also increasing net radiation. However, the combination of still air and cold grass canopy temperatures would facilitate formation of a stable boundary layer within, and vertically adjacent to, the grass canopy which would retard increases in the sensible heat flux.

There was no consistent pattern in soil temperature values relative to air temperature. During about half of the clear night periods evaluated it was warmer and about half cooler. It generally varied a degree across the measurement site with the site average of pooled dates being within a degree of air temperature (Table 1). The range over which the RFP temperature differed from soil surface temperature was greater than the range of the RFP–air temperature difference. The

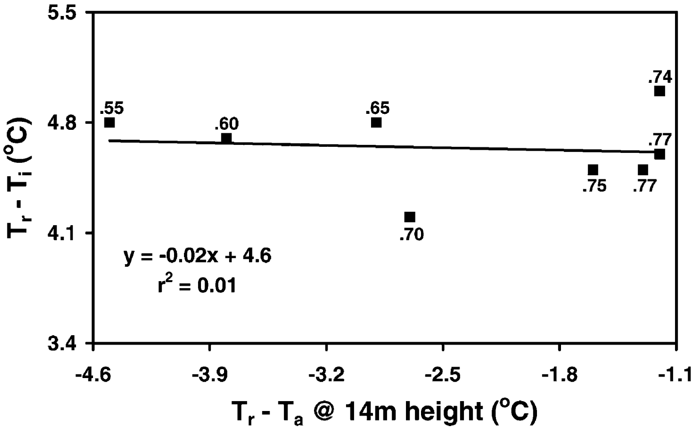

Fig. 5. The difference between RFP temperature and upward field-of-view temperature (T_i) as a function of the difference between RFP temperature and air temperature at 14 m height. The number adjacent to each data point is m_t for each respective site.

difference between the RFP temperature and air temperature was not correlated with the RFP–soil temperature difference indicating soil heat flux was not strongly influencing RFP temperature (Fig. 6) even at either extreme m_t value site. Surface soil temperature had much less impact on the potential for frost compared to the amount of clear sky unobscured by tree canopy.

There is the possibility is that the overhead temperature is underestimated due to thermal radiation not measured such as radiation from tree trunks, which dominate the lower field-of-view regions. Tree trunks have considerable thermal mass and could be warmer than air temperature at night. It might account for some of the constant difference between the RFP temperature and the overhead temperature between measurement sites within the silvopasture. This is something that needs to be measured in future research.

The regression equation for data plotted in Fig. 4 can be used to estimate open sky and maximum tree cover RFP temperature. If no trees obstructed the

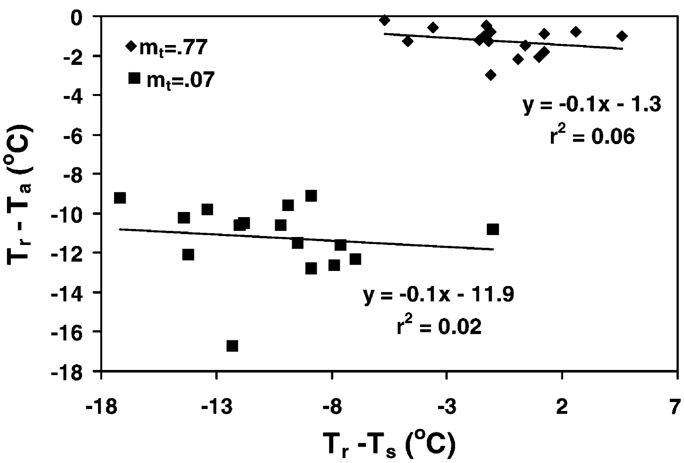

Fig. 6. The difference between RFP temperature and air temperature as a function of the difference between soil temperature and air temperature for sites, where $m_t = 0.07$ and 0.77.

horizon then RFP temperature should average 11.5 °C below air temperature during typical radiation frost conditions. Similarly, for RFP temperature to equal air temperature, only 80% tree canopy cover should be required.

The degree to which trees in this study provide frost protection exceeds values others have found for trees or shade cloth. Odin et al. (1984) measured a maximum of 2 °C temperature increase for saplings at 25 cm above ground level when growing under shelterwood. Caramori et al. (1996) measured coffee tree leaves up to 4 °C warmer under taller trees. Igarashi et al. (1993) and Scowcroft et al. (2000) measured from 2 to 5 °C higher temperatures under shade cloth. Only Teitel et al. (1996) measured comparable values with 9 °C temperature increases for leaves under aluminized 50% shade cloth compared to open sky crops.

Increases of 3–5 °C in daily minimum grass temperature were found under 400 stems ha^{-1} stands of *Pinus radiata* (D Don) (Hawke and Wedderburn, 1994). However, these data were not necessarily from nights with clear skies nor under frost conditions.

5. Conclusions

A considerable amount of silvopastoral research has been focused on the impact of shade on forage accumulation and quality (Kephart and Buxton, 1993; Devkota et al., 1997; Lin et al., 1999). However, forages may be adversely impacted by radiation frosts early and late in the growing season. The ability of silvopastures to extend the growing season during these periods as a result of trees protecting forages from radiation cooling, to which open pastures are subjected, appears to be substantial. Low growing, grazed forage canopies (5–15 cm) may experience temperatures over 11 °C warmer when the field-of-view is obscured by 80% conifer foliage compared to forages on level treeless sites under radiation frost conditions.

Because of the large angle of incident solar radiation during the spring and autumn, it is possible to design silvopastures with large spatial differences in daytime incident radiation, but little differences in night time radiation cooling. This would provide a mosaic of growing forages for grazing animals that varies in quantity and quality at a time when open fields could be composed largely of senesced leaves.

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